Probing the star formation epoch with Wilkinson Microwave Anisotropy Probe (WMAP) data and high-redshift QSOs

Jun'Ichi Yokoyama

Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka 560-0043, Japan

Abstract

Using the values of the cosmological parameters obtained from Wilkinson Microwave Anisotropy Probe (WMAP) and the cosmological chemical clock observed by high-redshift quasars, it is shown that star formation should have started by the redshift $z_F > 9.5$, and that z_F is sensitive only to $\Omega_{\rm m0}h^2$ in flat ΛCDM cosmology.

The first year data release of Wilkinson Microwave Anisotropy Probe (WMAP) has opened a new era of high precision cosmology (Bennet et al. 2003). As for the values of the cosmological parameters it has basically confirmed that of the concordance model with significantly smaller error bars than before. Together with the observation of nearly scale-invariant adiabatic fluctuations, the inflation-based flat ΛCDM model can be regarded as the primary candidate of the standard evolution model of our Universe.

Ever since Hubble's discovery of cosmic expansion (Hubble 1929), who concluded that the cosmic expansion rate was as large as $H_0 \simeq 500$km/s/Mpc, we encountered the cosmic age problem from time to time in the history of modern cosmology. The introduction of vacuum-like energy density with negative pressure such as cosmological constant Λ as inferred from the magnitude-redshift relation of high-redshift type Ia supernovae (Perlmutter et al. 1999; Riess et al. 1998) has reconciled a relatively large Hubble parameter $h = H_0/(100\text{km/s/Mpc}) \simeq 0.7$ (Freedmann et al. 2001) with a fairly large cosmic age $t_0 \gtrsim 13$Gyr. Indeed the cosmic age obtained by WMAP observations supplemented by other cosmological observations, $t_0 = 13.7 \pm 0.2$Gyr with $h = 0.71^{+0.04}_{-0.03}$, $\Omega_{\rm m0}h^2 = 0.135^{+0.008}_{-0.009}$, $\Omega_{\rm v0} = \Omega_{\rm tot0} - \Omega_{\rm m0}$, and $\Omega_{\rm tot0} = 1.02 \pm 0.02$ are in good agreement with astrophysical estimate of globular cluster age and cosmological nuclear chronology (Spergel et al. 2003). Here $\Omega_{\rm v0}$ denotes the current value of the vacuum-like energy density or dark energy in unit of the critical density.

Thus as far as the current Universe is concerned we have indeed the concordance of the cosmic age and various cosmological parameters at hand. However, the situation may change drasitically if we turn our attention to the high-redshift Universe. Indeed with the improved accuracy of current values of the cosmological parameters, we can calculate the cosmic age at redshift z, $t(z)$, more accurately. Comparing $t(z)$ with other measures of cosmic age at high-redshift we can obtain important cosmological and astrophysical information and constraints.

As for the latter we consider observation of Fe/Mg abundance ratio probed by high-redshift quasars. This quantity can serve as a cosmic chemical clock due to the difference of the origin (Hamann & Ferland 1993). That is, Fe is predominantly produced by type Ia supernovae whose precursor has a lifetime of ~ 1 Gyr or larger, while Mg and other alpha elements are produced from type II supernovae with much shorter time scale. Thus the ratio Fe/Mg at the redshift z indicates the time elapsed between the star formation epoch z_F and z.

Previously this measure was mainly used to constrain the values of cosmological parameters with particular emphasis on whether cosmological constant is nonvanishing (Yoshii, Tsujimoto, & Kawara 1998). But at the new era of precision cosmology with WMAP and other sophisticated observational tools we can extract useful information on z_F and chemical evolution models of the Universe as argued below.

Although the observational constraint of WMAP on the spatial curvature or the total energy density of the Universe still has a two percent uncertainty, $\Omega_{\rm tot0} = 1.02 \pm 0.02$, we assume $\Omega_{\rm tot0}$ is equal to unity with much higher accuracy, because we have good reasons to believe in standard inflation as argued above, which predicts $|\Omega_{\rm tot0} - 1| < Q \simeq 5 \times 10^{-6}$ with Q being the quadrupole anisotropy of cosmic microwave background radiation (Kashlinsky, Tkachev & Frieman 1994). Then, in the spatially flat Robertson-Walker spacetime with the scale factor $a(t)$, cosmic age at redshift z is given by

$$t\left(z\right) = \int \frac{da}{\dot{a}} = \frac{1}{H_0}\int_z^\infty \frac{dz}{(1+z)E(z)},$$
$$E(z) = \left[\Omega_{\rm m0}(1+z)^3 + \Omega_{\rm v0}f(z)\right]^{1/2}, \qquad (1)$$

where $f(z)$ is a function which specifies the evolution of dark energy component. If it has a constant index of equation of state, $w_v \equiv \rho_v/p_v$, where ρ and p denote energy density and pressure respectively, one finds $f(z) = (1+z)^{3(1+w_v)}$. The pure cosmological constant corresponds to $w_v = -1$. Below we mainly consider this case because it is theoretically well-motivated (Yokoyama 2002a,b) and observationally supported among many other candidates of dark energy (Yokoyama 2003). In the above expression we have neglected radiation component, which is a good approximation in the range of redshifts we consider.

Several authors have calculated time evolution of Fe/Mg ratio using a chemical evolution model. For example, Yoshii, Tsujimoto & Kawara (1998) calculated its evolution based on the model of Yoshii, Tsujimoto & Nomoto (1996) with the following three basic ingredients. The first one is the star formation rate $C(t)$ parametrized as $C(t) = \nu_k\left[f_g(t)\right]^k$ where $f_g(t)$ is the gas fraction and ν_k and k are parameters. As the standard model they choose $k = 1$ and $\nu_{k=1} = 7.6\mathrm{Gyr}^{-1}$ as inferred from metal abundance in quasar host galaxies (Hamann & Ferland 1993). The second is the initial stellar mass function (IMF) which is assumed to be time-invariant with a spectrum $\phi(m)dm \propto m^{-x}dm$ for $0.05M_\odot \leq m \leq 50M_\odot$ with $x = 1.35$ based on Tsujimoto et al. (1997). The third and the most important ingredient is the fraction, A, and the lifetime, t_{Ia}, of the progenitors that eventually produce SNe Ia, and their time spread. They adopt $A = 0.055$ for $m = 3-8M_\odot$ and $A = 0$ outside this mass range as a standard value. t_{Ia} is obtained from the break in [O/Fe] observed at [Fe/H]~ -1 in the solar neighborhood (Yoshii, Tsujimoto & Nomoto 1996) and taken as $t_{Ia} = 1.5$ Gyr, while its spread function, $g(t_{Ia})$, is modeled as a power-law $g(t_{Ia}) \propto t_{Ia}^\gamma$. In practice, they take $\gamma = 0$ and $g(t_{Ia}) \neq 0$ for $t_{Ia} = 1-3$ Gyr, again to match the observational features of [O/Fe] and [Fe/H].

As for the observation, Yoshii, Tsujimoto and Kawara used UV-optical spectrum of QSO B1422+231 at $z = 3.62$ and found FeII(UV+opt)/MgII $\lambda\lambda$ 2796, 2804 flux ratio to be 12.2 ± 3.9. Assuming this ratio traces the abundance ratio Fe/Mg, they obtained [Mg/Fe]$= -0.61^{+0.12+0.16}_{-0.30-0.12}$, which, according to their standard evolution model, implies that the time elapsed from z_F to $z = 3.62$ is given by

$$\Delta t_{z=3.62} \equiv t(z=3.62) - t(z_F) = 1.50 \text{ Gyr}. \qquad (2)$$

They have also considered possible modification of their standard model and concluded that the lower bound is 1.3 Gyr, namely, $\Delta t_{z=3.62} \geq 1.3$ Gyr, which may be realized for a higher value of $A \gtrsim 0.08$. As is seen in Table 1 of Yoshii, Tsujimoto and Kawara (1998), modification of other model parameters tends to increase Δt.

This quasar is by no means the only QSO whose flux ratio FeII/MgII has been observed. Thompson, Hall and Elston (1999) analyzed spectra of 12 high-redshift quasars to probe evolution of FeII/MgII ratio. As a result they found no decline in the iron abundance even at $z = 4.47$ and concluded that about 1Gyr had passed from z_F to $z = 4.47$. Dietrich et al. (2002), on the other hand, observed six high-redshift QSOs with $z = 3310 - 3.488$ and basically confirmed the conclusion of Yoshii, Tsujimoto and Kawara (1998), namely, $\Delta t_{z\approx 3.4} \approx 1.5$ Gyr.

Comparing these values with the formula (1) calculated with the improved values of cosmological parameters obtained with WMAP, we can find constraint on the epoch of star formation z_F. Specifically we consider the three possible tests on z_F as argued above, to draw contours of z_F corresponding to $\Delta t_{z=3.62} = 1.3$ Gyr, $\Delta t_{z=3.62} = 1.5$ Gyr and $\Delta t_{z=4.77} = 1.0$ Gyr.

Figures 1-3 depict these contour on an $\Omega_{\rm m0} - H_0$ plane. As is seen there the condition $\Delta t_{z=3.62} = 1.5$ Gyr is more stringent than that $\Delta t_{z=4.77} = 1.0$ Gyr. For the most likely value of the cosmological parameters obtained by WMAP, $h = 0.71$ and $\Omega_{\rm m0} = 0.268$ under the assumption that $\Omega_{\rm v0} = 1 - \Omega_{\rm m0}$, we find $z_F = 10.13$ from $\Delta t_{z=3.62} = 1.3$ Gyr, $z_F = 14.98$ from $\Delta t_{z=3.62} = 1.5$ Gyr, and $z_F = 11.91$ from $\Delta t_{z=4.77} = 1.0$ Gyr. Thus significant star formation before $z_F > 10$ is inferred. In principle we could yield even more stringent constraint than $z_F = 14.98$, if we applied Yoshii et al's model (1998) to Thompson et al's data (1999), but we remain conservative here, allowing the room for uncertainty in chemical evolution models.

More interesting are contour maps depicted on a $\Omega_{\rm m0}h^2 - H_0$ plane, which are shown in figs. 4-6. As is seen there in the range of cosmological parameters under consideration z_F is insensitive to H_0 and depends only on $\Omega_{\rm m0}h^2$. Thus for $\Omega_{\rm m0}h^2 = 0.135^{+0.008}_{-0.009}$, we obtain $z_F = 10.1^{+0.7}_{-0.6}$ from $\Delta t_{z=3.62} = 1.3$ Gyr, $z_F = 15.0^{+1.9}_{-1.7}$ from $\Delta t_{z=3.62} = 1.5$ Gyr, and $z_F = 11.9 \pm 0.7$ from $\Delta t_{z=4.77} = 1.0$ Gyr. We may therefore conclude $z_F > 9.5$ in the flat ΛCDM Universe with the cosmological parameters obtained by combination of WMAP and other measures.

Finally we briefly mention the case dark energy has a softer equation of state $w > -1$ than the cosmological constant. For a constant coefficient w, WMAP has obtained a constraint $w < -0.78$ (Spergel et al. 2003). Dark energy with a softer equation of state tends to require star formation at higher redshift, although the change is modest. For example, for $w = -0.8$, $h = 0.71$, and $\Omega_{\rm m0} = 0.268$ we find $z_F = 10.36$, 15.57, and 12.10, respectively instead of $z_F = 10.13$, 14.98, and 11.91 for the case of the cosmological constant as discussed above.

In conclusion we have pointed out that in the new era of precision cosmology we can obtain some useful information on the evolution of the high-redshift Universe from the cosmological chemical clock rather than constraining current values of cosmological parameters with them. We have shown that the epoch of star formation z_F should satisfy $z_F > 9.5$ and that it is sensitive only to $\Omega_{\rm m0}h^2$ in the context of the standard flat ΛCDM cosmology. This constraint would bring about interesting implication to formation of galaxies that host quasars.

This work was partially supported by the JSPS Grant-in-Aid for Scientific Research No. 13640285.

FIGURES

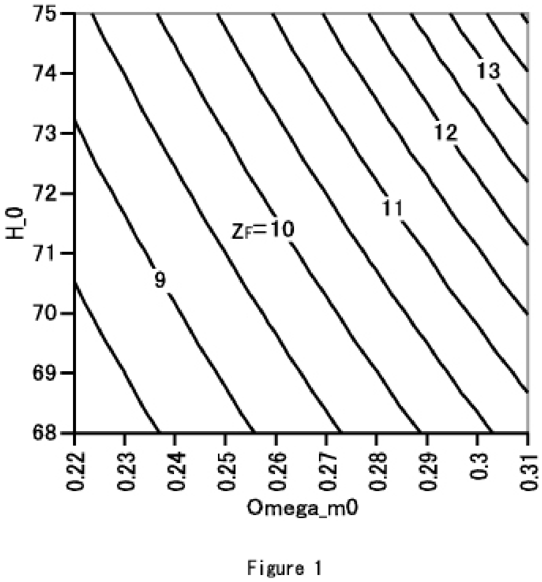

FIG. 1. Contour map of z_F which satisfies $\Delta t_{z=3.62} = 1.3$ Gyr as a function of $\Omega_{\mathrm{m}0}$ and H_0.

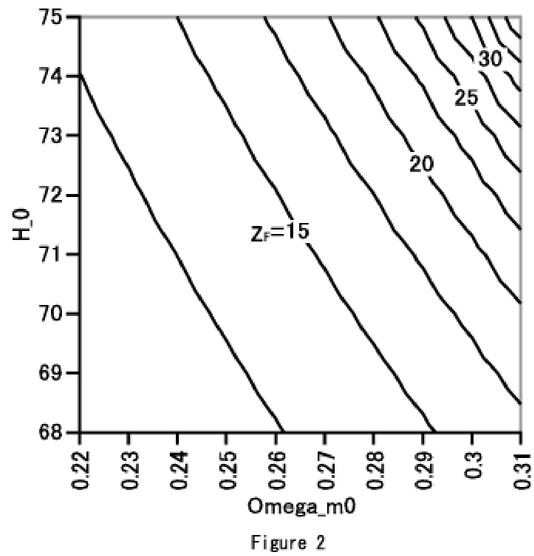

FIG. 2. Contour map of z_F which satisfies $\Delta t_{z=3.62} = 1.5$ Gyr as a function of $\Omega_{\mathrm{m}0}$ and H_0.

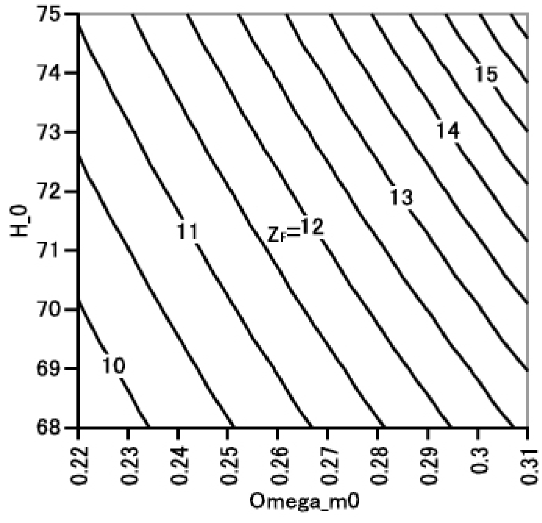

FIG. 3. Contour map of z_F which satisfies $\Delta t_{z=4.77} = 1.0$ Gyr as a function of $\Omega_{\rm m0}$ and H_0.

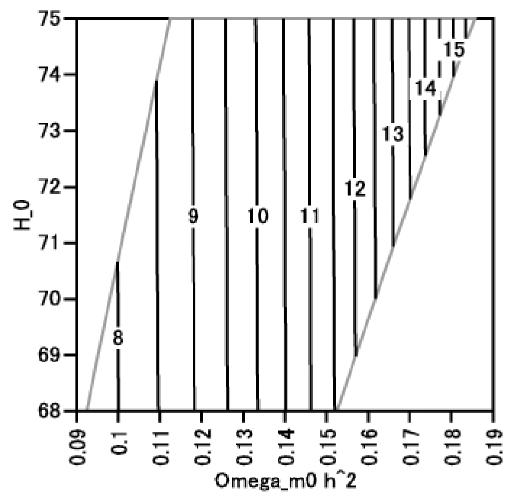

FIG. 4. Contour map of z_F which satisfies $\Delta t_{z=3.62} = 1.3$ Gyr as a function of $\Omega_{\rm m0} h^2$ and H_0.

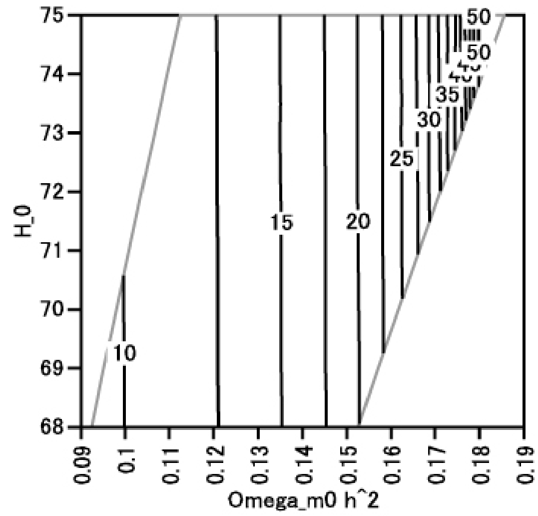

Figure 5

FIG. 5. Contour map of z_F which satisfies $\Delta t_{z=3.62} = 1.5$ Gyr as a function of $\Omega_{\rm m0}h^2$ and H_0.

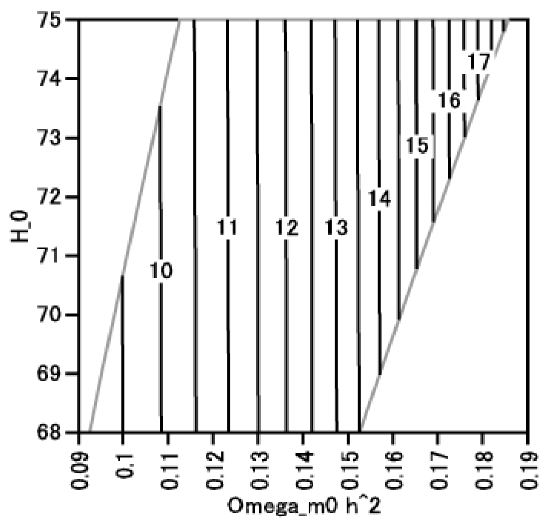

Figure 6

FIG. 6. Contour map of z_F which satisfies $\Delta t_{z=4.77} = 1.0$ Gyr as a function of $\Omega_{\rm m0}h^2$ and H_0.

REFERENCES

Bennett, C.L., Halpern, M., Hinshaw, G., Jarosik, N., Kogut, A., Limon, M., Meyer, S.S., Page, L., Spergel, D.N. et al., 2003, astro-ph/0302207

Dietrich, M., Appenzeller, I., Vestergaard, M., and Wagner, S.J., 2002, ApJ, **564**, 581

Freedman, W.L., Madore, B.F., Gibson, B.K., Ferrarese, L., Kelson, D.D., Sakai, S., Mould, J.R., Kennicutt, R.C. et al., 2001, ApJ, **553**, 47

Hamann, F. and Ferland, G., 1993, ApJ, **418**, 11

Hubble, E.P, 1929, Proc. Nat. Acad. Sci, **15**, 168

Kashlinsky, A., Tkachev, I.I., Frieman, J., 1994, Phys. Rev. Lett., **73**, 1582

Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R.A., Nugent, P., Castro, P.G., Deustua, S., Fabbro, S., Goobar, A., et al., 1999, ApJ, **517**, 565

Riess, A.G., Nugent, P.E., Gilliland, R.L., Schmidt, B.P., Tonry, J., Dickinson, M., Thompson, R.I., Budavari, T.S., et al., 1998 AJ, **116**, 1009

Spergel, D.N., Verde, L., Peiris, H.V., Komatsu, E., Nolta, M.R., Bennett, C.L., Halpern, M., Hinshaw, G., et al., 2003, astro-ph/0302209

Thompson, K.L., Hill, G.J., Elston, R., 1999, ApJ, **515**, 487

Tsujimoto, T., Yoshii, Y., Nomoto, K., Matteucci, F., Thielemann, F.-K., & Hashimoto, M., 1997, ApJ, **483**, 228

Yoshii, Y., Tsujimoto, T., and Nomoto, K., 1996, ApJ, **462**, 266

Yoshii, Y., Tsujimoto, T., and Kawara, K., 1998, ApJL, **507**, L113

Yokoyama, J. 2002a, Phys. Rev. Lett., **88**, 151302

Yokoyama, J. 2002b, Int. J. Mod. Phys., **D11**, 1603

Yokoyama, J. 2003, In Proc. 12th workshop on general relativity and gravitation, eds. Y. Eriguchi and M. Shibata. (University of Tokyo)